# Steric sea level variations over 2004-2010 as a function of region and depth: Inference on the mass component variability in the North Atlantic Ocean

W. Llovel, B. Meyssignac, A. Cazenave

# Steric sea level variations over 2004–2010 as a function of region and depth: Inference on the mass component variability in the North Atlantic Ocean

W. Llovel,[1,2] B. Meyssignac,[1] and A. Cazenave[1]

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[1] We investigate the regional-ocean depth layer (down to 2000 m) contributions to global mean steric sea level from January 2004 to March 2010, using Argo-based ocean temperature and salinity data from the SCRIPPS Oceanographic Institution database. We find that Indian ocean warming is almost compensated by Atlantic ocean cooling, so that the total global mean steric sea level increases only slightly over the considered period (0.35 ± 0.30 mm/yr). Salinity variations also contribute, at lower rate, to the observed steric compensation. Meanwhile, the Pacific steric sea level increases only slightly (0.35 ± 0.25 mm/yr). In the North Atlantic region, the mass component (estimated by the difference between satellite altimetry-based minus steric sea level over the same area) is negatively correlated over 2004–2010 with the steric component. During that period, North Atlantic sea level variability seems mostly driven by the North Atlantic Oscillation (NAO). This is unlike during the previous years (1997 to 2004), a period during which we observe significant correlation between North Atlantic sea level and El Nino-Southern Oscillation (ENSO), with positive sea level corresponding to ENSO cold phases (La Nina). **Citation:** Llovel, W., B. Meyssignac, and A. Cazenave (2011), Steric sea level variations over 2004–2010 as a function of region and depth: Inference on the mass component variability in the North Atlantic Ocean, *Geophys. Res. Lett.*, *38*, L15608, doi:10.1029/2011GL047411.

## 1. Introduction

[2] Measuring sea level change and understanding its causes is a major goal in climate research, considering the potentially highly negative consequences of sea level rise under global warming. According to the Intergovernmental Panel on Climate Change-4th Assessment Report (IPCC-AR4), global mean sea level rise during the 1993–2003 decade amounted to 3.1 ± 0.7 mm/yr (2-sigma uncertainty), with ~50% attributed to thermal expansion and ~40% due to water mass input from ice sheet and glacier ice mass loss [*Bindoff et al.*, 2007]. Since about 2004, slowdown in thermal expansion rate has been reported by a number of investigators using Argo profiling floats data [*Willis et al.*, 2008, 2010; *Levitus et al.*, 2009; *Cazenave et al.*, 2009; *Leuliette and Miller*, 2009; *Llovel et al.*, 2010]. However, estimated rates of rise from the different studies are highly scattered, likely a result of too short time spans of analysis, different data processing strategies, etc. [e.g., *Lyman et al.*, 2010]. Nevertheless, as shown by *Llovel et al.* [2010] using different in situ temperature and salinity databases (mostly from Argo), there is clear evidence of slower rate of steric (i.e., thermosteric plus halosteric) sea level rise in the recent years. Such a result motivated us to investigate further the steric sea level at regional scale and as a function of ocean depth. For that purpose, we study the behavior of the steric sea level over the past few years in the three main ocean basins and estimate the contributions of ocean layers at different depths. We finally look at sea level and mass component in the North Atlantic Ocean.

## 2. Data Sets

### 2.1. Satellite Altimetry Data

[3] In this study, we use the Ssalto/duacs multi-mission sea level products provided by CLS/AVISO (downloaded at the website: http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products/global/msla/index.html). As described on the website, data are provided with two levels of resolution on a Mercator grid: (1) 1/3° × 1/3° and (2) 1° × 1°. Here, we choose the first option resampled on a Cartesian grid at 1/4° × 1/4° resolution. These sea level products are available at weekly interval. The data used in this study span from January 2004 to March 2010. Over the studied time span, the data are principally based on Jason-1 and Jason-2, but Envisat and GFO data are also used with lower weight. Most updated geophysical and environmental corrections have been applied to the data, including the inverted barometer correction (see *Ablain et al.* [2009] for details).

### 2.2. Argo Data

[4] We consider Argo-based temperature T and salinity S fields of the SCRIPPS Institution of Oceanography database (as shown by *Llovel et al.* [2010], compared to other available data bases, the SCRIPPS data have good temporal coverage, cover a larger depth range and are given at monthly interval). The SCRIPPS data can be downloaded from the http://www.argo.ucsd.edu/Gridded_Field.html website [*Roemmich and Gilson*, 2009]. We have computed thermosteric (T anomalies only), halosteric (S anomalies only) and steric (T plus S anomalies) gridded sea level time series in three different layers (0–300 m, 300–700 m and 700–2000 m depth), over the ocean domain up to 65°N and 65°S of latitude, at monthly interval, on 1° × 1° mesh, over the time span from January 2004 to March 2010.

[5] As no errors are provided with the SCRIPPS T/S data, we have also computed steric/thermosteric/halosteric sea level time series using three additional databases (NOAA, IPRC databases, as by *Llovel et al.* [2010] and JAMSTEC data-

[1]LEGOS, CNES, CNRS, IRD, UPS, Toulouse, France.
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.


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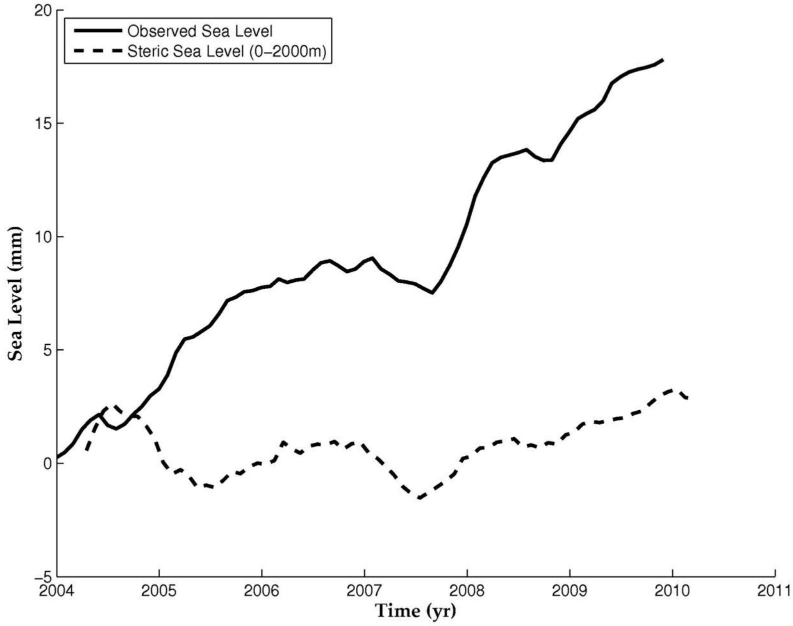


**Figure 1.** Observed altimetry-based (black curve) and steric (dashed black curve) global mean sea level between 2004–2010 computed between 65°S and 65°N latitude. Seasonal signal removed and 7-month running smoothing applied.

base), and estimated the data errors from the dispersion between the different time series (see *Llovel et al.* [2010] for details).

## 3. Results

### 3.1. Region-Depth Steric Sea Level Variations

[6] Figure 1 shows the global mean steric sea level over the time span of analysis (January 2004 to March 2010). The altimetry-based (i.e., observed) global mean sea level is superimposed for comparison. The global mean steric trend (based on T, S data from surface to 2000 m depth) over the period amounts to 0.35 ± 0.3 mm/yr. As mentioned above, the uncertainty is based on the root-mean squares difference between values estimated from individual databases (note that it is compatible with errors provided by *Lyman et al.* [2010], for the ocean heat content from different Argo data bases). In the remainder of the paper, steric/thermosteric/halosteric errors are always based on this approach.

[7] The observed (altimetry-based) rate of sea level rise over the same time span is 2.8 ± 0.4 mm/yr. The 0.4 mm/yr uncertainty is based on that of *Ablain et al.* [2009] from an assessment of all sources of errors affecting the altimetry-derived mean sea level trend.

[8] Figure 2 displays the regional mean steric (Figures 2a–2c) and thermosteric (Figures 2d–2f) sea level over Indian, Pacific and Atlantic ocean sectors in three different layers: 0–300 m (blue curves), 300–700 m (red curves) and 700–2000 m (black curves). The sector boundaries are as defined as follows: Indian Ocean (65°S-30°N latitude, 40°E-110°E longitude); Pacific Ocean (65°S-65°N latitude, 110°E-290°E longitude); Atlantic Ocean (65°S-65°N latitude, 290°E-40°E longitude). Seasonal signals have been removed at each grid mesh through a least squares fit analysis. A 7-month running smoothing has been applied to the time series. Figure 2 reveals a large positive steric trend of the Indian Ocean upper layer (0–700 m). For comparing the trend value to the global mean steric trend, it is necessary to weight it by the ratio of the ocean box area to the total oceanic area considered in this study (±65° latitude). In the following, all quoted trends are weighted trends using the ratio of the considered area to the total area. The weighted trend for the Indian upper layers (0–700 m) amounts to ~1 ± 0.3 mm/yr. The deeper layer (700–2000 m) also shows steric sea level increase but with smaller magnitude. The value for the 0–2000 m depth range is +1.2 ± 0.4 mm/yr. It represents the contribution of the Indian Ocean box to the total steric trend. Comparison with the thermosteric sea level suggests that the steric trend is mainly due to temperature, hence ocean warming. In addition to a positive trend, the upper layer steric/thermosteric sea level (0–300 m) shows large interannual variability associated with the Indian Ocean Dipole – IOD- [*Cai et al.*, 2009; *Schott et al.*, 2009]. The IOD index is superimposed (dashed grey curve) on the thermosteric upper layer curve of the Indian Ocean contribution. The correlation between the two curves is 0.9.

[9] In the Pacific Ocean, the regional mean steric/thermosteric sea level shows small trends both in the upper and deeper layers. Over the 0–2000 m depth range, the Pacific steric trend amounts to 0.35 ± 0.25 mm/yr –weighted value-. Large, ENSO (El Niño-Southern Oscillation)-related interannual variability is observed. The correlation with the Southern Oscillation Index (SOI) superimposed to the thermosteric upper layer curve (dashed grey curve) equals to 0.7. The interannual variability of the recent years steric sea level in the Indian and tropical Pacific was studied in more detail by *Llovel et al.* [2010].

[10] In the Atlantic Ocean, regional mean steric/thermosteric sea level curves show negative trends, especially in the upper layer. Slight negative trends are also seen in the deeper layers. However, unlike the other oceans, the halosteric component (i.e., due to salinity variations) plays a significant role here (not shown), resulting in partial compensation in the steric sea level, likely associated to heat and fresh water, circulation-

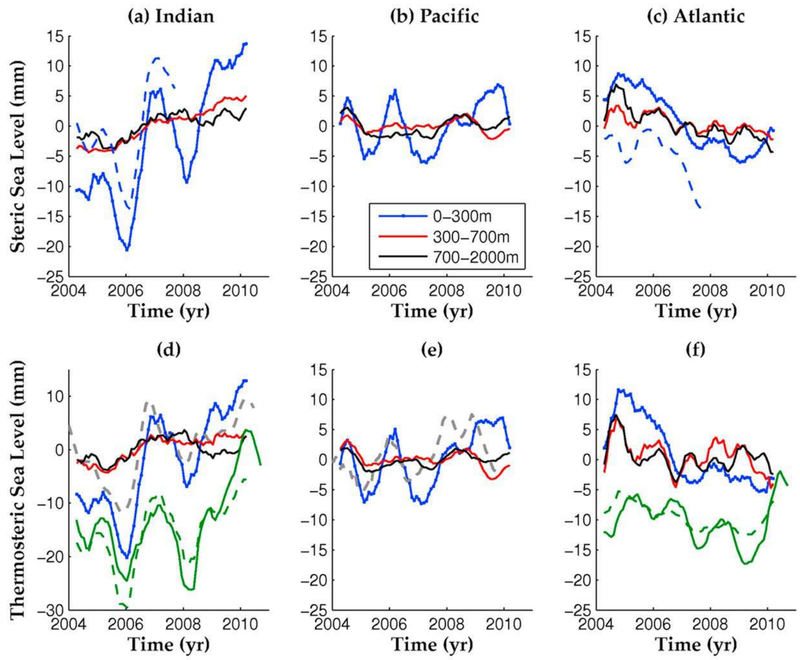


**Figure 2.** Regional mean steric (upper panels) and thermosteric (lover panels) sea level over 2004–2010, over the Indian, Pacific and Atlantic Ocean boxes for different layers: 0–300 m (blue curves), 300–700 m (red curves) and 700–2000 m (black curves). Seasonal signal removed and 7-month running smoothing applied. Panels are labeled a to f. DRAKKAR-based regional mean steric sea level (0–300 m) are superimposed on panels a and c (dashed blue curves). IOD index and SOI (both grey dashed curves) are superimposed on thermosteric sea level curves for Indian Ocean (panel d) and Pacific Ocean (panel e) respectively. Regional mean SST (dashed green curve) and Argo–based regional thermosteric sea level (over 0–100 m depth, solid green curve) are superimposed in panels d and f.

driven redistribution and fresh water input from land ice melt and river runoff. The Atlantic Ocean weighted steric trend (0–2000 m depth range) amounts to −1.0 ± 0.35 mm/yr.

[11] If we compare the area-weighted steric trends of the three ocean boxes, we note opposite contributions between Indian and Atlantic Oceans (of +1.2 ± 0.4 mm/yr and −1.0 ± 0.35 mm/yr respectively), with near compensation between the two regions. As the Pacific Ocean steric trend is small over the studied period, we get a small value for the total steric trend (of ~0.5 mm/yr) (note that the sum of the three box contributions is slightly larger than the observed total trend of 0.35 mm/yr; this is because the sum of the box areas does not exactly coincide with the total domain). Computed steric and thermosteric weighted trends are summarized in Table 1. The global values are also given.

[12] In order to check whether the apparent warming and cooling of the Indian and Atlantic oceans (hence compensation) may not result from instrumental Argo floats bias, we compared Argo-based thermosteric/steric sea level in these two ocean basins with two types of independent data: (1) the in situ and satellite sea surface temperature (SST) analysis [*Reynolds et al.*, 2002], and (2) the steric sea level from a general ocean circulation model –OGCM- (the DRAKKAR/NEMO -B83 run- model meteorologically forced by the CORE dataset assembled by W. Large [*Large and Yeager*, 2004], and no data assimilation [*Barnier et al.*, 2006; *Dussin et al.*, 2009]). SST data are provided monthly on 1°x1° grids. Data were geographically averaged over the ocean domains defined above over the time span considered in this study. The averaged SST was then compared to Argo-based thermosteric sea level of the 0–100 m upper ocean layer in these two basins. Similarly, we computed the mean steric sea level over the 0–300 m upper ocean layer from the DRAKKAR model outputs (which end in early 2007). Corresponding results are shown in Figures 2a and 2c for DRAKKAR (dashed blue curves) and Figures 2d and 2f for SST (dashed green curves). We note very high correlation (>0.85 for all cases) between Argo-based steric/thermosteric sea level and totally inde-

**Table 1.** Regional Mean Steric and Thermosteric Sea Level Trends Weighted by the Ratio of the Box Area to the Total Ocean Area for the Indian, Pacific, Atlantic, North Atlantic Oceans and the Sum of the Three Considered Oceans

| Jan. 2004–Mar. 2010 | Indian Ocean (65°S-30°N, 40°E-110°E) | Pacific Ocean (65°S-650N, 110°E-290°E) | Atlantic Ocean (65°S-65°N, 290°E-40°E | North Atlantic (0-65°N, 290°E-40°E) | Total |
|---|---|---|---|---|---|
| Area weighted steric sea level trend (mm/yr) (0–2000 m depth range) | +1.2 ± 0.4 | +0.35 ± 0.25 | −1.0 ± 0.35 | −0.32± 0.25 | 0.55 ± 0.5 |
| Area weighted thermosteric sea level trend (mm/yr) (0–2000 m depth range) | +1.0 ± 0.4 | +0.52 ± 0.25 | −0.8 ± 0.35 | −0.23 ± 0.25 | 0.72 ± 0.5 |

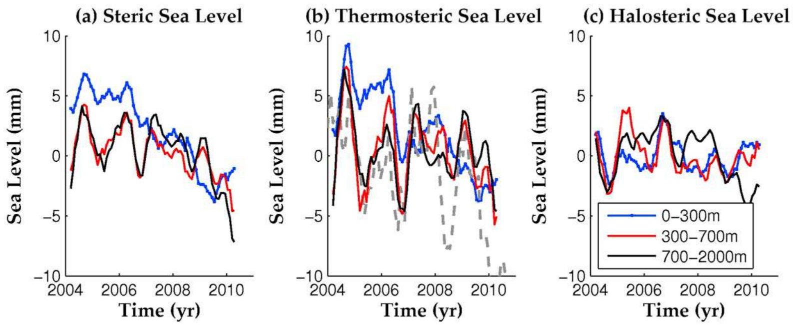


**Figure 3.** Regional mean (a) steric, (b) thermosteric and (c) halosteric sea level over 2004–2010 over the North Atlantic box at different ocean layers: 0–300 m (blue curves), 300–700 m (red curves) and 700–2000 m (black curves). Seasonal signal removed and 7-month running smoothing applied. NAO (grey dashed curve) is superimposed to thermosteric sea level curves (Figure 3b).

pendent data from an OGCM and SST products. This gives us confidence that the trends reported in the Indian and Atlantic oceans with Argo data are not due to artifacts or instrumental bias of the Argo floats.

### 3.2. Steric and Mass Components of the Observed Sea Level in the North Atlantic

[13] We now focus on the North Atlantic (equator to 65°N, from 290°E to 40°E longitude). Figures 3a–3c show corresponding steric/thermosteric/halosteric sea level (blue, red and black curves respectively) at the same 3 layers and between 0° to 65° latitude (seasonal signal removed). A clear negative trend is observed in each layer. These short-term trends suggest recent cooling of the region as negative trend is also seen in the thermosteric sea level. The total weighted North Atlantic steric trend (0–2000 m depth range) amounts to −0.32 ± 0.25 mm/yr.

[14] In the lower layers (700–2000 m), steric and thermosteric curves reflect high interannual variability, linked to the North Atlantic Oscillation-NAO (see the NAO index –dashed grey curve- superimposed to the thermosteric curve in Figure 3b).

[15] Figure 4 shows observed, altimetry-based mean sea level over the North Atlantic sector (solid black curve) since 1997. Mean steric (doted-solid blue curve) and thermosteric (solid blue curve) sea level over the same domain are also shown since 2004 (as computed in this study using T, S data down to 2000 m depth). In Figure 4 is also shown the difference (called below ‘mass component’) between observed (altimetry-based) and steric sea level over the North Atlantic

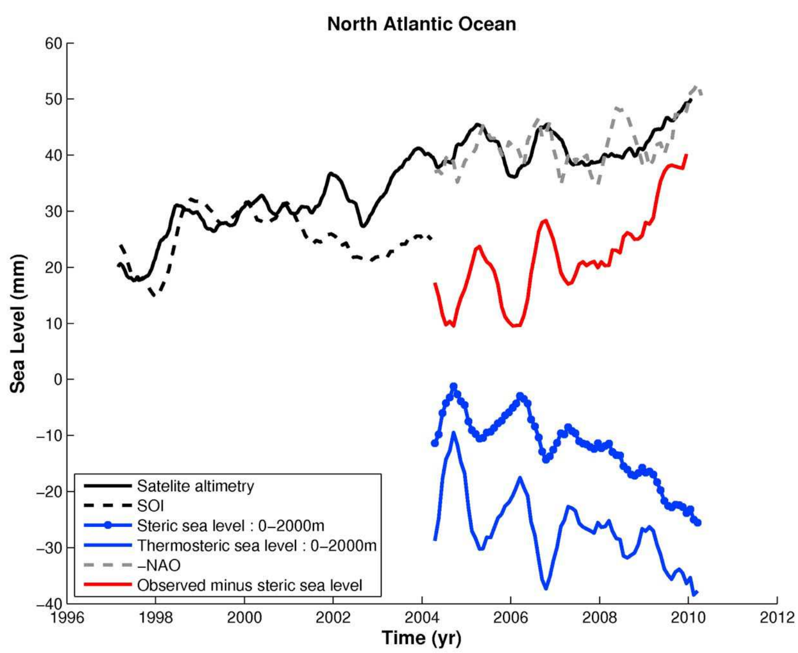


**Figure 4.** Observed (altimetry-based) mean sea level for the North Atlantic Ocean box (0° to 65°N, 290°E to 40°E) (solid black curve) between 1997–2010; mean steric (doted-solid blue curve), thermosteric sea level (solid blue curve), and mass component (observed minus steric sea level, solid red curve) over the 2004–2010 for the same region. Seasonal signal removed and 7-month running smoothing applied. Steric and thermosteric sea level correspond to the 0–2000 m depth range. Black and grey dashed curves superimposed to observed sea level curve represent SOI and inverse NAO respectively.

sector. The seasonal signal has been removed from all curves and a 7-month smoothing is also applied. While the steric sea level (0–2000 m depth) shows a decreasing trend as discussed above, the mass component shows a positive trend. Both curves appear negatively correlated (correlation coefficient of −0.95).

[16] As shown above, North Atlantic thermosteric sea level is correlated with the NAO index (Figure 3b). We now note that the mass component and the total (altimetry-based) sea level are negatively correlated with NAO during the 2004–2010 time span (positive sea level corresponding to NAO negative phase and inversely). This is illustrated in Figure 4 where the inverse NAO index is superimposed to sea level. Prior to 2004, the North Atlantic sea level is dominantly influenced by ENSO: in Figure 4, we superimposed the Southern Oscillation Index (SOI) (with 7-month smoothing; dashed black curve) to the North Atlantic altimetry-based sea level curve over 1997–2004. The correlation between the two curves amounts to 0.65 between 1997–2001, with positive sea level during La Nina, the ENSO cold phase (corresponding to positive SOI). However the correlation decreases to 0.25 over 1997-2004.

[17] Several previous studies have reported a clear connection between tropical Pacific and tropical North Atlantic sea surface temperature (SST) variability [*Enfield and Mayer*, 1997; *Latif and Grotzner*, 2000] during ENSO events, with warming of the tropical eastern Pacific being associated with warming of the tropical North Atlantic, 4–6 months later [*Giannini et al.*, 2001]. Such tropical North Atlantic SST variability appears in turn to be linked to rainfall conditions over Amazonia [*Yoon and Zeng*, 2010]. Increased rainfall over northeastern Amazonia during La Nina events may eventually extend over the tropical North Atlantic as a result of an eastward shift of precipitation patterns. Increased rainfall over northeastern Amazonia during La Nina events may eventually extend over the tropical North Atlantic as a result of an eastward shift of precipitation patterns, possibly increasing the mass component and sea level. Fresh water input into the tropical Atlantic due to increased runoff from the Amazon River may be another cause, the two effects eventually working concurrently. Further analysis is needed to understand the mechanism responsible for the observed increase in North Atlantic sea level during La Nina events, and more generally the link between tropical Pacific, Amazon hydrology and tropical Atlantic during ENSO events.

[18] While our study suggests some influence of the strong 1997–1999 ENSO event on the North Atlantic sea level, it also reveals that beyond 2004, NAO was the main driver of the interannual variability of the North Atlantic sea level, acting both on the steric and mass components.

## 4. Conclusion

[19] The present analysis reports different behaviors of the steric sea level depending on the ocean basin over the 2004–2010 time span. The Indian Ocean shows significant ocean warming between 0 and 2000 m depth, while the Atlantic Ocean shows cooling during the same period. In the Atlantic region, slight upper ocean salinity variation is also observed, which suggests large-scale ocean circulation changes and heat and fresh water redistribution are causing the observed steric variations. In the Pacific Ocean, significant trend is noticed and large interannual variability is also observed in the upper layer linked to ENSO events.

[20] Indian Ocean warming and Atlantic Ocean cooling more or less compensate each other during 2004–2010 time span, explaining the recent low observed rate of the steric sea level.

[21] In the North Atlantic, we find that the mass component (deduced from the difference between altimetry-based and steric sea level) is negatively correlated to the steric sea level. We also find that North Atlantic sea level interannual variability was influenced by ENSO during 1997–2004, but since 2004, the NAO influence dominates. Further studies are necessary to understand the mechanisms responsible for these observations.

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A. Cazenave and B. Meyssignac, LEGOS, CNES, CNRS, IRD, UPS, 14 av. Edouard Belin, F-31400 Toulouse CEDEX, France.

W. Llovel, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125, USA. (william.llovel@jpl.nasa.gov)